

# Greenland Ice Sheet

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## Highlights

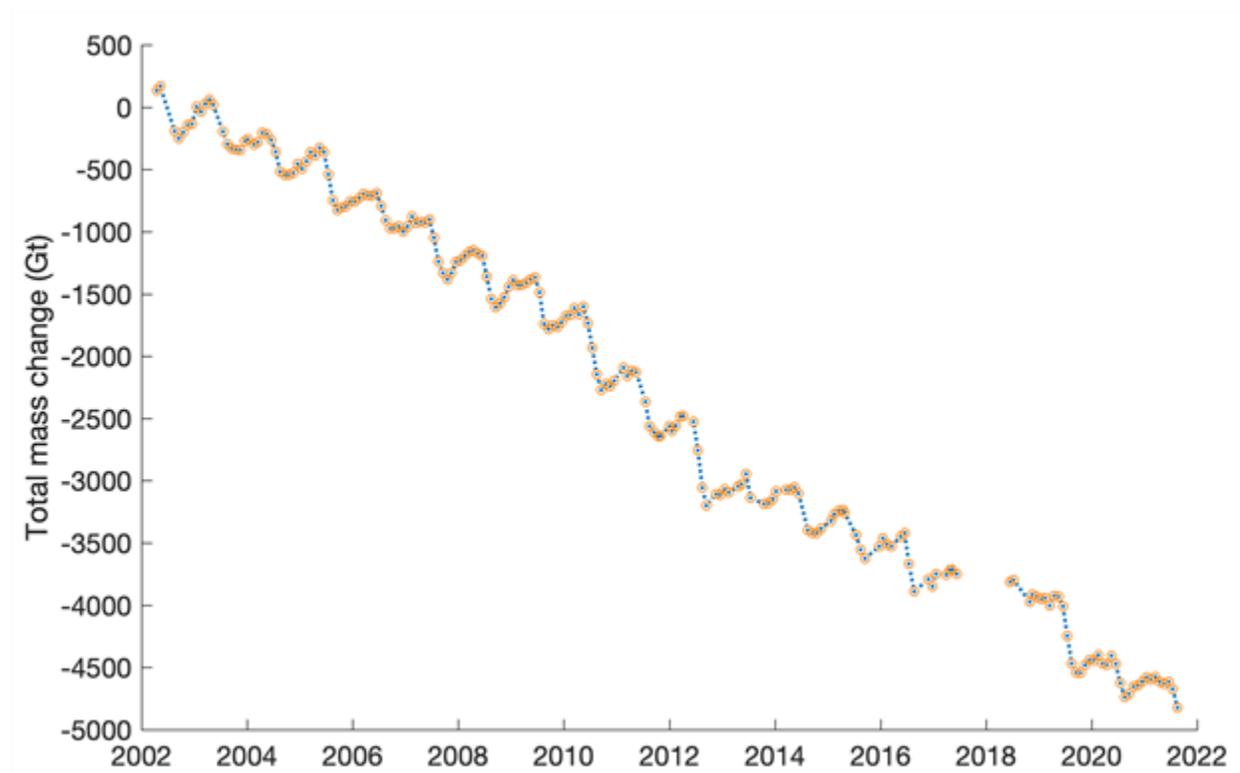
- Greenland ice sheet total mass change for 1 September 2020 to 31 August 2021 was  $-85 \pm 16$  Gt, 179 Gt less than the 2002-21 average of  $-264 \pm 12$  Gt yr<sup>-1</sup>.
- High variability characterized 2021 surface melting with a two-week long August period of increased melt and bare ice exposure contrasting with low June and July melt conditions. An overall average melt obscured strongly contrasting spatial and temporal melt patterns.
- On 14 August 2021, Greenland experienced the latest date of an extreme melt event (>50% area) within the 43-year satellite record, including the first reported rainfall at Summit Station, Greenland.

## Introduction

The Greenland ice sheet covers  $\sim 1.63$  million km<sup>2</sup> and contains ice equivalent to 7.4 m of eustatic sea level rise (Morlighem et al. 2017). Following decades of relative stability, the ice sheet has now lost mass almost every year since 1998, with tied years of record ice loss in 2012 and 2019 (Mankoff et al. 2021). Ice loss is exposing land, adding substantial freshwater into the ocean, and raising sea levels globally (Moon et al. 2020; Mankoff et al. 2020a; IMBIE Team 2020).

Total Greenland ice sheet mass balance is the sum of 1) the surface mass balance, which combines accumulated snow across the ice sheet with ice loss via surface melt and runoff, and 2) solid ice discharge via calving at tidewater glaciers. Surface melt in particular is sensitive to atmospheric and ice sheet surface conditions, and is a major component of ice loss (ablation). During the 2020-21 ice sheet balance year, spanning 1 September to 31 August, the total Greenland ice sheet mass change was  $-85 \pm 16$  Gt of ice as measured by the GRACE-FO satellite (Fig. 1). This is equivalent to  $\sim 0.2$  mm of

sea level rise, not including ongoing thermal expansion (IPCC 2021). The 2020-21 total mass balance year had 179 Gt less mass loss than the 2002-21 average of  $-264 \pm 12 \text{ Gt yr}^{-1}$ .

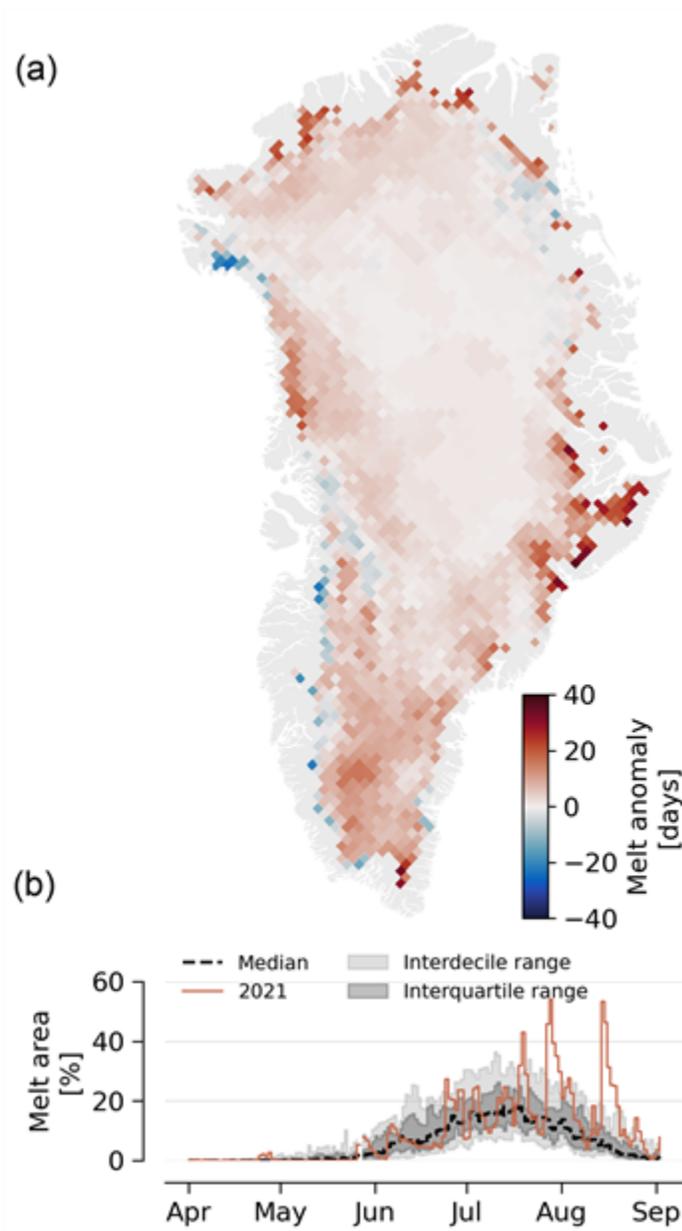


**Fig. 1.** Total mass change (Gt) of the Greenland ice sheet from April 2002 to August 2021 determined from GRACE (2002-17) and GRACE-FO (2018-Present) satellite data.

## Surface temperature, melt, and ablation

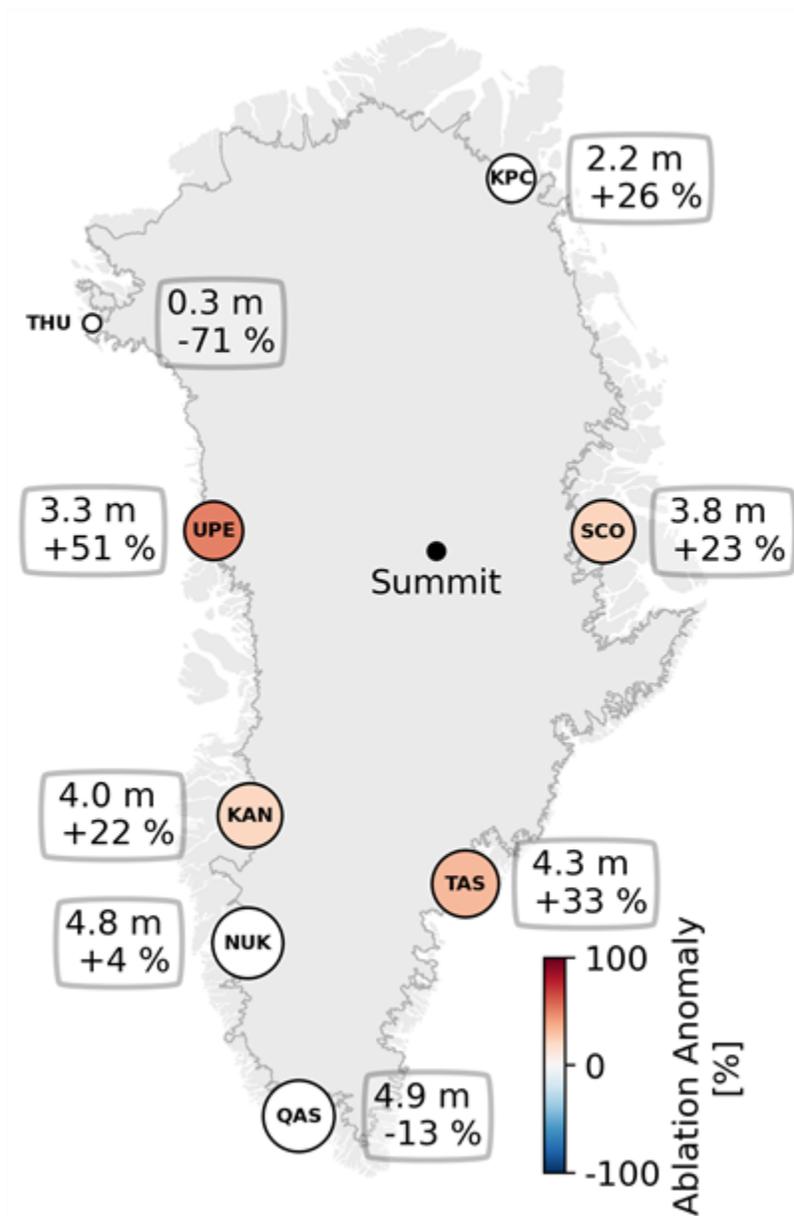
Surface temperature observations at 15 terrestrial DMI weather stations (with record start dates spanning from 1784 to 1991) recorded near or above average temperatures throughout the balance year. Temperature anomalies were generally highest in winter (December-February), exceeding one standard deviation at 11 of the 15 stations. A new summer (June-August) high temperature record was set at the Danmarkshavn station in northeast Greenland and July-only heat records were set at several other northeast stations. Tasiilaq, in southeastern Greenland, set a new August high temperature.

Except for an above-average melt event on 27 April, the ice sheet daily melt extent as measured by satellites remained low until 26 May and through mid-summer remained mostly within the 1981-2010 10th to 90th percentiles (Fig. 2). In situ, on-ice PROMICE automated weather stations recorded temperatures within  $\pm 1$  standard deviation for June and July. Late July and August, however, included three extreme melt episodes. The first, on 19 July, had melt across 702,000 km<sup>2</sup> (~43%) of the ice sheet surface. A second melt event on 28 July extended across 54% of the ice sheet surface, and a third melt episode concentrated on 14 August had 53% melt area and reached the highest ice sheet elevations (National Science Foundation's (NSF) Summit Station, 3216 m). All PROMICE weather stations along the ice sheet periphery recorded above-average air temperatures during all three events.



**Fig. 2.** (a) 2021 melt anomaly (in number of melting days) with respect to the 1981-2010 reference period, (b) Surface melt extent as a percentage of the ice sheet area during 2021 (solid red). Data derived from SSMIS satellite data.

For the full ablation season, PROMICE ablation measurements around the ice sheet margin indicate significantly above-average ablation along the central western and eastern coasts (Fig. 3).



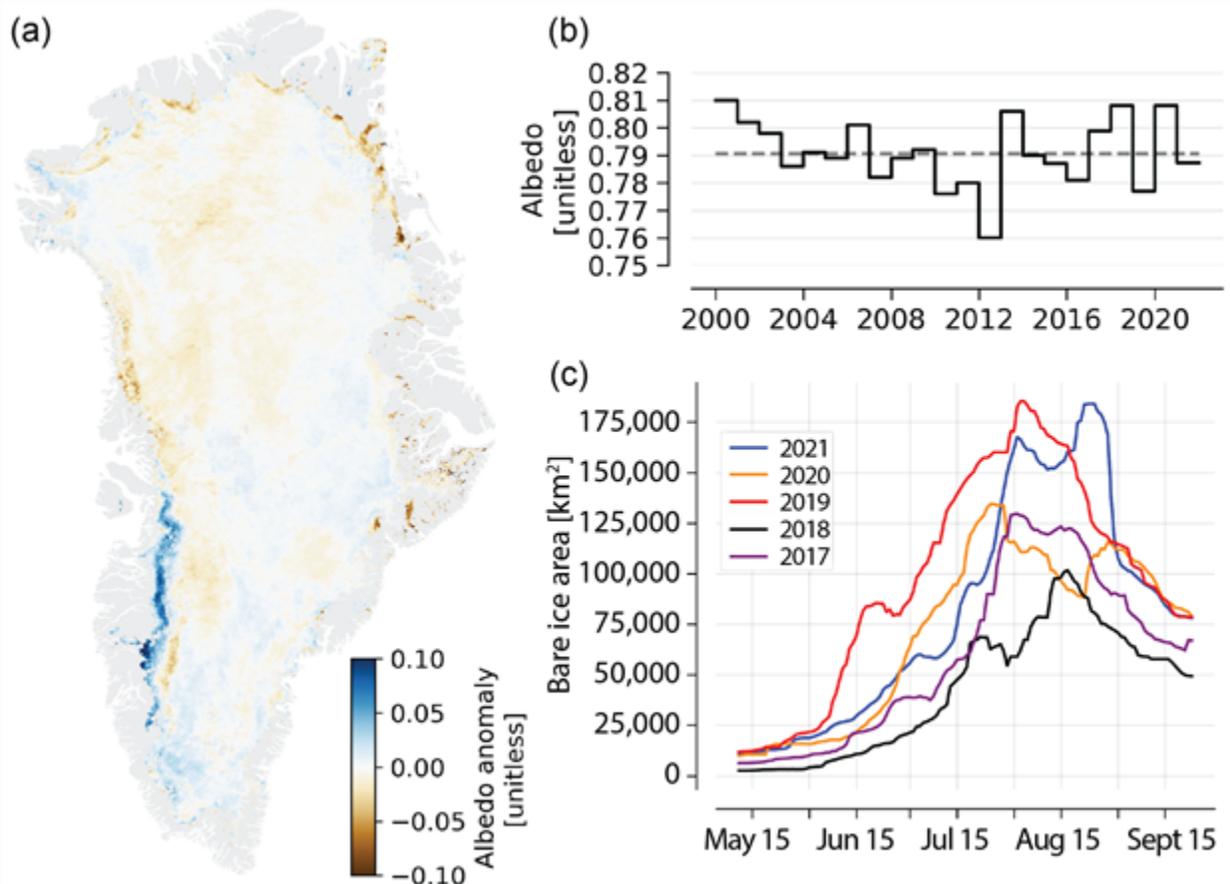
**Fig. 3.** Net ablation in 2021 measured by PROMICE weather transects and referenced to the 1981-2010 standard period. Circle size is scaled to the ablation in meters (m) of ice equivalent, and color scaled with anomaly value. White circles indicate anomaly values not exceeding methodological and measurement uncertainty. Stations are: Thule (THU), Upernavik (UPE), Kangerlussuaq (KAN), Nuuk (NUK), Qassimuit (QAS), Tasiliq (TAS), Scorebysund (SCO), and Kronprins Christians Land (KPC). NSF Summit Station is also marked.

### Albedo and bare ice area

Ice sheet reflectivity (albedo) strongly modulates surface melt. When the ice sheet surface is dark (low albedo) the surface absorbs more sunlight, leading to the possibility of earlier melt onset and/or enhanced melting. Contributors to low albedo include loss of snow cover revealing bare ice, snow grain growth, and organic and inorganic surface material like microbes or black carbon. In contrast, a bright surface, for example from fresh snow, increases albedo and reduces melt potential. The snow-covered

to bare glacial ice transition produces a strong albedo shift, making bare ice area a useful observational metric (Wehrlé et al. 2021).

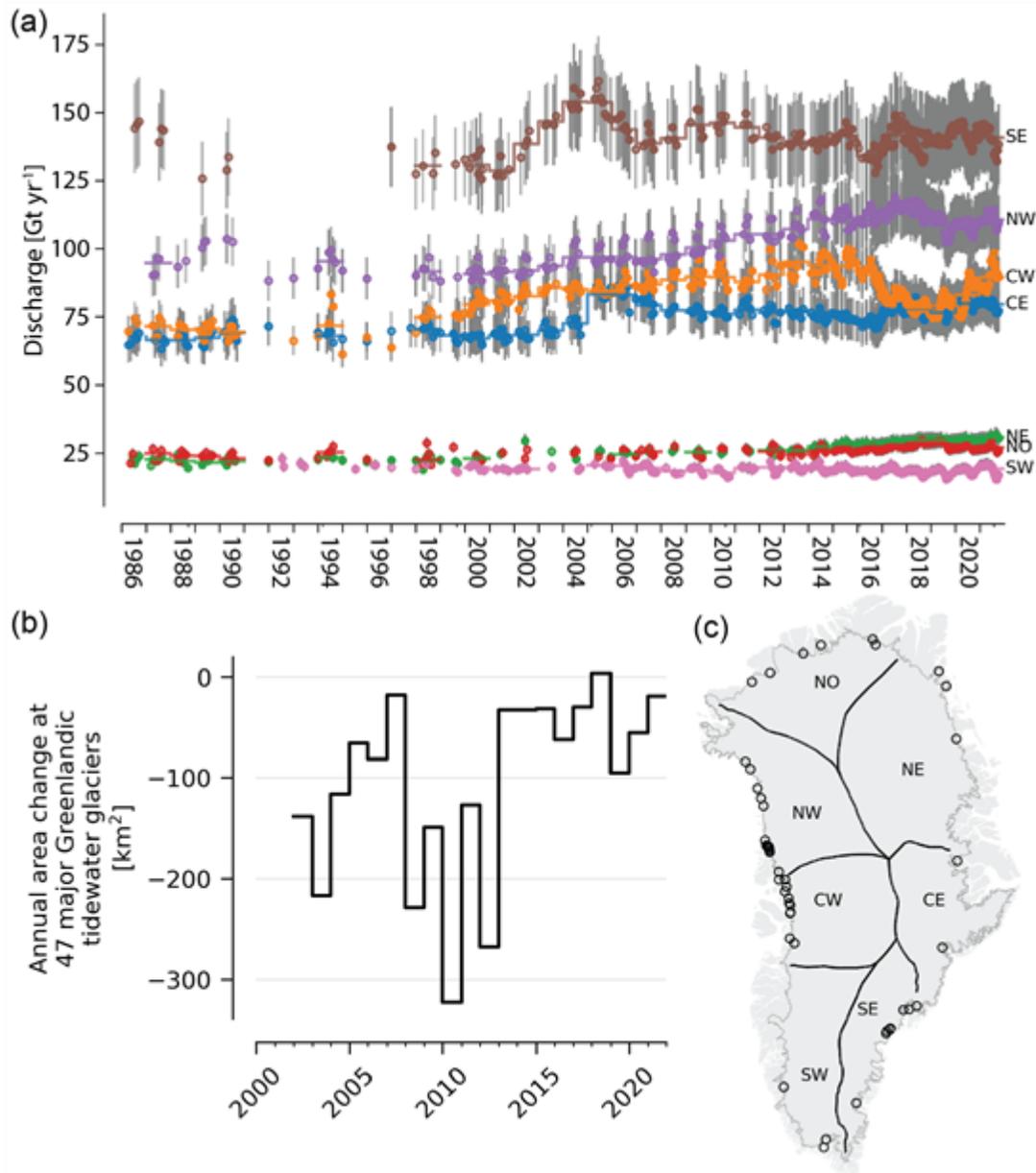
The average June through August 2021 ice sheet albedo was at the 2000-21 average, due in part to an above-average (bright) July, offset by a below-average (dark) August. Regionally, the southwest was brighter than normal from delayed melting (Fig. 4a,b) and darker than normal across the northern ice sheet. During mid-August, bare ice area (Fig. 4c) reached extremely low values equal to those in 2019, a record-tying ice loss year. August 2021 also had the latest peak in bare ice area during the past five years (2017-21). Note that local ablation (Fig. 3) and albedo anomalies (Fig. 4a) may not intuitively align due to factors such as summer snowfall, surface atmospheric conditions, extreme melt events, etc.



**Fig. 4.** (a) Albedo anomaly for summer 2021, relative to a 2000-09 reference period, (b) Time series for average Greenland ice sheet summer albedo, (c) Bare ice area from Sentinel-3. Data for (a) and (b) from MODIS.

## Solid ice loss and tidewater area change

Year-to-year variability in ice loss from calving is lower than surface melt variability (Mankoff et al. 2020b). Nonetheless, an inter-decadal  $\sim 10\%$  discharge increase is apparent. For 1981-2010, the average total discharge was  $\sim 444 \pm 47 \text{ Gt yr}^{-1}$ , while average discharge during 2010-19 was  $\sim 487 \pm 46 \text{ Gt yr}^{-1}$ . As of November, solid ice discharge for 2021 reached an average of  $497 \pm 48 \text{ Gt yr}^{-1}$ , with the largest contributions from the southeast, followed by the northwest (Fig. 5a,c).



**Fig. 5.** (a) Solid ice discharge ( $\text{Gt yr}^{-1}$ ; gray bars show  $\pm 10\%$  uncertainty range), (b) Total area change at 47 major Greenlandic tidewater glaciers, (c) Regions for solid ice discharge for (a): north (NO), northeast (NE), central east (CE), southeast (SE), southwest (SW), central west (CW), and northwest (NW), and sampled glaciers for (b) indicated with open circles.

If solid ice loss through calving is more rapid than replacement from ice flow, the glacier front retreats and glacier area is lost. For 2020-21, net tidewater glacier surface area loss due to glacier front retreat was  $-18.9 \text{ km}^2$  for 47 major and representative Greenland tidewater glaciers (Fig. 5b,c), substantially lower than the mean annual loss of  $-103.3 \text{ km}^2$  for these glaciers since 2002 (Andersen et al. 2019).

## Extreme August melt event

Atmospheric circulation strongly modulates surface melt via the thermal and radiative budgets. August 2021 had two notable atmospheric anomalies. In early August, persistent high-pressure conditions

centered over the ice sheet promoted enhanced melting (see essay [Surface Air Temperature](#)). These conditions were similar to those that generated the 2012 and 2019 melt records but did not produce a 2021 extreme melt event. In mid-August, an atmospheric event associated with the transport of moisture at high elevations promoted the exceptional rainfall event at Summit. In this case, it was not an increase in solar radiation promoting melting but the heat and moisture influx. Though the near-surface processes that led to enhanced melting in early and mid-August 2021 were different, enhanced melting in both cases was associated with a disruption and increased sinuosity of the polar vortex.

Based on the 1978-present satellite record, the melt event centered on 14 August 2021 was the latest time during the ablation season that more than half of the ice sheet (>815,000 km<sup>2</sup>) experienced surface melt. Summer 2021 is only the second year on record (along with 2012) with more than one melt event exceeding this threshold. This was also the first time that rainfall was reported at NSF's Summit Station (3216 m above sea level) since its operation started in 1989, though surface melt (without rainfall) was observed in 1995, 2012, and 2019. The 1995-to-present melt event frequency at Summit (4 events in 27 years) is in contrast to the average of one event per 153 years for the 10,000 years prior to 1950, derived from ice core data (Alley and Anandakrishnan 1995). Scientists are now installing rain gauges at interior ice sheet weather stations; rain gauges on a new-generation GC-Net station at South Dome (2850 m) recorded three distinct summer 2021 rainfall events.

## Methods

Total mass change is measured indirectly by the GRACE (Gravity Recovery and Climate Experiment, 2002-17) and GRACE-FO (Follow On, 2018-present) satellite missions by detecting gravity anomalies. Technical Notes (TN) are hosted at <https://podaac-tools.jpl.nasa.gov/drive/files/allData>.

Direct weather observations are provided via 15 Danish Meteorological Institute (DMI) weather stations with records beginning from 1784 (Nuuk) to 1991 (Summit) and 8 automatic weather station transects from the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) at the Geological Survey of Greenland and Denmark (GEUS). DMI stations are located on land, with most coastal and some within fjords, with Summit data provided by NOAA GEOSummit. PROMICE transects, located on the ice sheet, also provide surface ablation (following van As et al. 2016). Surface melt duration and extent measurements are derived from daily Special Sensor Microwave Imager/Sounder (SSMIS) 37 GHz, horizontally polarized passive microwave radiometer satellite data (Mote 2007).

NASA MODIS satellite data provide multi-decadal albedo monitoring (Box et al. 2017). The Sentinel-3 SICE product is now being used to monitor bare ice area (Kokhanovsky et al. 2020; Wehrlé et al. 2021).

PROMICE combines ice thickness estimates with ice velocity measurements based on Sentinel-1 satellite data to create a high temporal resolution solid ice discharge product integrated over Greenland (following Mankoff et al. 2020b).

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